Using pulsars to limit the existence of a gravitational wave background

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Abstract. Gravitational waves passing the Earth induce signals in pulsar timing residuals that are potentially detectable using modern pulsar timing observations. It has been predicted that merging supermassive black hole systems will cause an isotropic background of gravitational waves. Pulsar timing observations will soon be able to provide useful constraints on models for its formation. Future experiments will either detect this background or rule out all existing models. Various cosmic string theories and inflationary era models have also been proposed that predict gravitational wave backgrounds, but the amplitude of the background in these models is not well constrained. We review new techniques to limit the existence of any gravitational wave background, provide results obtained using data taken as part of the Parkes Pulsar Timing Array project and describe the implications of these new upper limits.

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INTRODUCTION

Since February 2004, 20 millisecond pulsars have been regularly observed at three frequencies (close to 600, 1400 and 3000 MHz) for the Parkes Pulsar Timing Array (PPTA) project (Manchester, these proceedings, Manchester 2006, Hobbs 2005). The main goal of the project is to use these observations to make the first direct detection of gravitational waves (GWs).

Pulsar timing experiments are most sensitive to GW signals with ultra-low (nHz) frequencies. Potentially detectable individual sources include supermassive ($\sim 10^9 M_\odot$) binary black hole systems and GW bursts from cosmic string cusps. Isotropic GW backgrounds may exist that have been formed from binary supermassive black holes, cosmic strings or relic GWs from the big bang. In Figure 1 the expected sensitivities obtainable by various pulsar timing arrays are compared with the expected power spectra for various sources. As shown in the figure, our existing data-sets are already sufficient to detect backgrounds predicted by some cosmic string models, but are not yet sufficient to detect a GW background due to binary black-holes in galaxies or relic GWs (see also Jenet et al. 2005).

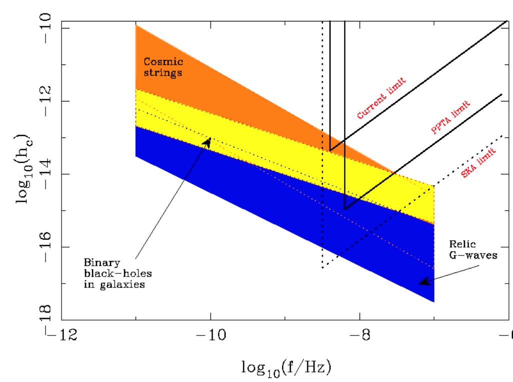

FIGURE 1. Power spectra of possible sources. The PPTA and the SKA limits are the sensitivities expected at the completion of the Parkes Pulsar Timing Array project after five years of observing and, with reasonable assumptions, for a ten year project involving the SKA respectively.

SOURCES OF GRAVITATIONAL WAVE BACKGROUNDS

An isotropic GW background can be described by its characteristic strain spectrum as a function of frequency,

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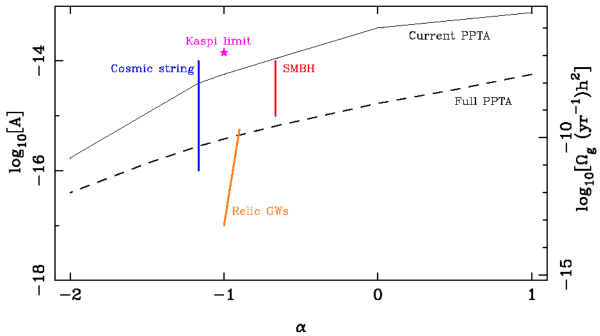

FIGURE 2. The solid line indicates our current limits on GW backgrounds of specified α. The dashed line underneath indicates the expected limits within 5 years. The near vertical lines give predicted background amplitudes. The "star"-symbol indicates the earlier limit obtained by Kaspi et al. (1994).

f, and amplitude A:

$$h_c(f) = A \left(\frac{f}{\mathrm{yr}^{-1}}\right)^{\alpha}. \quad (1)$$

The spectral exponent, α, depends upon the physical processes generating the background. Jenet et al. (2005) review the three likely sources of a GW background currently known:

- Merging galaxies: Jaffe & Backer (2003), Wyithe & Loeb (2003), Enoki et al. (2004) and Sesana et al. (2004) have investigated backgrounds generated by the merging and coalescence of supermassive binary black hole systems in the centres of merging galaxies. Models predict that such a background can be described with $\alpha = -2/3$ and $10^{-15} < A < 10^{-14}$.
- Cosmic strings: Vilenkin (1981) and Damour & Vilenkin (2005) have shown that oscillating cosmic string loops will produce GW radiation. A network of such strings may be detectable as a stochastic background. Damour & Vilenkin (2005) describe a model in which $\alpha = -7/6$ and the amplitude is dependent upon the cosmic string tension. This tension is rather uncertain, but the GW amplitude is likely to lie between $10^{-17} < A < 10^{-14}$.
- Relic GWs: Such backgrounds could have been generated in the inflationary era of the universe (Grishchuk 2005) and have $\alpha \approx -1$. The amplitude of any such background is highly model dependent.

The predicted ranges for α and A for the different backgrounds are shown as near-vertical dotted lines in Figure 2.

AN UPPER BOUND ON THE BACKGROUND

Numerous papers have described methods of placing limits on the amplitude of a GW background using pulsar timing observations (see Kaspi et al. 1994, McHugh et al. 1996, Thorsett & Dewey 1996). However, none of this work included all the details of the pulsar timing analysis, such as the fitting of a pulsar's astrometic, spin and orbital parameters, the irregular sampling of the observations and the non-Gaussian statistics of the observations.

Jenet et al. (2006) use classical signal detection theory (Helstrom, 1968) to obtain an upper bound on the GW background amplitude. The measured signal is assumed to be pure noise with a white spectrum. The summation of the lowest frequency "bins" in a Gram-Schmidt orthogonal power spectrum is used as a detection statistic, but the method would work with any detection statistic. The detection threshold is set to provide a false alarm probability of 0.1%. In setting this threshold new noise realisations from the observations are obtained by shuffling the white timing residuals. Thus this technique does not assume that the signal is Gaussian. Finally, simulated GW background signals are added to the shuffled observations, processed through TEMPO2, to find an amplitude at which the probability of detection is 95%. This amplitude is the upper bound.

The limits derived by this technique, using seven PPTA pulsars, are the most stringent yet placed on the strength of a GW background (see solid line in Figure 2). These limits constrain cosmic string models, merger rates of massive black holes and models of the inflationary era of the universe. If the PPTA project achieves its aim of obtaining timing residuals for 20 pulsars with an rms of 100 ns over 5 years of observing, and no GW background has been detected, then the limits obtained will be those given by the dashed line in Figure 2. These new limits would rule out all existing models for a GW background due to merging supermassive black holes, the majority of cosmic string models and would start to constrain models of the inflationary era.

Future telescopes, such as the Square Kilometre Array (SKA), will be able to make pulsar observations with far greater sensitivity. They will be able to detect and study the expected GW background or rule out all existing models for such backgrounds.

AN IMPROVED UPPER BOUND

The Jenet et al. (2006) method suffers from two problems. It does not give the lowest possible upper bound and it relies on the observed spectrum being white. This

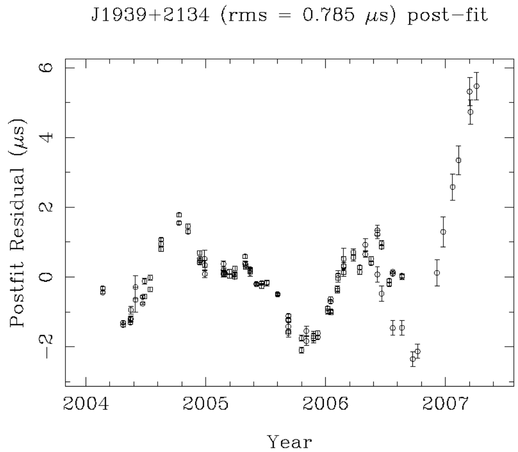

FIGURE 3. The timing residuals for PSR B1937+21 showing the existence of significant timing noise.

method provides the amplitude of the largest GW that would not be detected (at the 99.9% certainty level) 5% of the time. However, as pointed out by Allen & Romano (1999), we need the amplitude of the largest GW for which the detection statistic would exceed the *observed* value 95% of the time. Since the observed value is much lower than the 0.1% detection level this would give a lower upper bound.

Non-white timing noise is ubiquitous in young pulsars, but it had been thought to be absent in many of the recycled millisecond pulsars. Unfortunately, as timing precision improves, it is becoming apparent that all pulsars (including those in our sample) show non-white timing noise. Some of this is due to dispersion measure variations caused by turbulence in the interstellar plasma (You et al. 2007). This can be partially corrected using multiple frequency observations, but unexplained non-white timing noise remains. This situation limits the applicability of the Jenet et al. (2006) technique and casts some doubt on the bounds derived from it. As an extreme example of timing noise we show, in Figure 3, the timing residuals for PSR B1937+21. Each observation can be made with exquisite precision (uncertainties < 100 ns are regularly achieved), but the rms timing residual after TEMPO2 fitting across the entire data span is large. Even though TEMPO2 has been used to fit for the standard pulsar astrometric, orbital and rotational parameters (which removes low-frequency trends, power at the pulsar's orbital frequency and an annual term), large low frequency variations are readily apparent in Figure 3.

In order to avoid assuming that the residuals are white noise, we assume nothing about the measured signal. It could be entirely due to GWs. We then use simulated GWs alone, processed through TEMPO2 to find an amplitude at which the simulated detection statistic falls below the observed value only 5% of the time. Even though we have neglected the probability that most (or indeed all) of the signal is noise, our new method provides a lower upper bound than the Jenet et al. (2006) technique. If more information is known about the noise, then the noise can be simulated and added into the simulation thereby reducing the upper bound.

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